

## Correction Magnets for the Fermilab Recycler Ring

GW Foster, HD Glass, C Gattuso, DE Johnson, CS Mishra, JT Volk, M-J Yang

FNAL, Batavia, IL 60510, USA

### Abstract

In the commissioning of the Fermilab Recycler ring the need for higher order corrector magnets in the regions near beam transfers was discovered. Three types of permanent magnet skew quadrupoles, and two types of permanent magnet sextupoles were designed and built. This paper describes the need for these magnets, the design, assembly, and magnetic measurements.

### 1. Introduction

The Fermilab recycler<sup>1</sup> is an 8 GeV anti-proton storage ring. The magnets for this storage ring are made of combination gradient magnets and quadrupoles<sup>2</sup>. All main magnets are hybrid permanent magnets with low carbon steel pole pieces and strontium ferrite to provide the field<sup>3</sup>. As operational experience with the Recycler has been gained, the need for higher order correction elements became apparent. Beam measurements revealed a skew quad component in the field region of the Lambertsons<sup>4</sup> used for extraction and injection between the Main Injector and Recycler. To minimize the resultant x-y coupling, a pair of skew quads were installed in the transfer line. The transverse placement of the Lambertsons in the Recycler ring dictated that the closed orbit must be offset (~25 mm) through the field free region of the Lambertson and the adjacent ring gradient magnets. The ring gradient magnets have built in sextupole that feeds down into a quadrupole field due to the orbit offset. This feed down disturbs the focusing properties of both the injection and circulating lattice. A set of three permanent magnet sextupoles were installed to cancel the integrated sextupole component of the adjacent gradient magnets

### 2. Skew Quadrupoles

The Lambertson magnets use strontium ferrite to generate the required field. The field free region is made by gun boring a hole through the Lambertson base plate. Due to the variation of the residual B field in the ferrite, a skew quadrupole moment is induced in the bend field region of the Lambertson. To compensate this

skew quad, several different types of corrector magnets were developed. Although each met the integrated gradient requirement of 0.39 Tesla-meter/meter, the rectangular (2b) design was installed in each Recycler to Main Injector transport line due geometrical constraints.

### 2a. Panofsky Quad

The use of current sheets to make a quadrupole focusing lenses was first suggested W. K. H. "Pief" Panofsky. These current sheets can also be realized by the use of permanent magnet material. For the

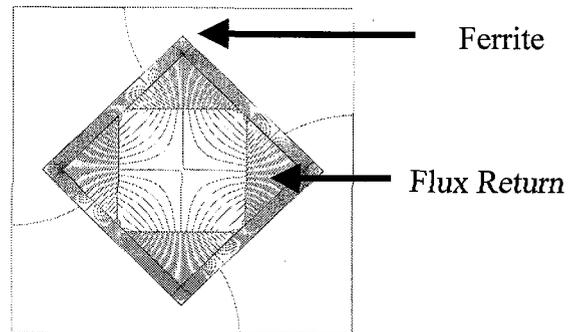


Figure 1 PANDIRA model of Panofsky quadrupole

Panofsky style quad a 101.6 mm square steel flux return was built and triangular shaped grade 8-strontium ferrite magnets were put in the corners (Figure 1). The open aperture of the magnet, 101.6 mm by 50.8 mm, was set by the size of the beam pipe. A two dimensional magnetic model was made in PANDIRA. A Br of 3800 Gauss and Hc of 3500 oersteds were used in the PANDIRA file. The field was predicted to be 4.96 Tesla/m, with an integrated field of 0.5 Tesla-meter/meter predicted for bricks 0.1 m long. The magnet was measured at Fermilab's Magnet Test Facility using a tangential coil. The integrated field was found to be 0.471 Tesla-meter/meter or 5.8% low. This may be explained as loss of field through the ends, which is not modeled in the 2-D codes.

To adjust the integral gradients, triangular pieces of steel in the same cross-section as the upper and lower magnets (101.6 mm x 50.8mm) and 0.9 mm thick were added at both ends top and bottom to reduce the

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volk@fnal.gov

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field. Figure 2 shows the relation between integral gradient versus the total number of steel shims.

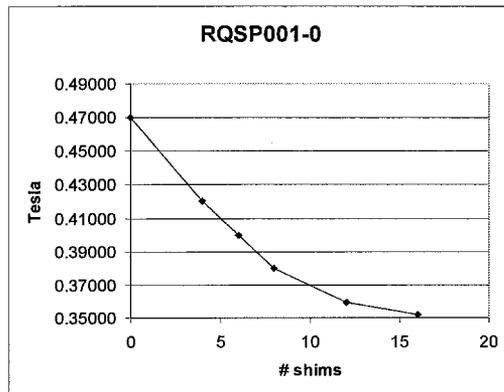


Figure 2 Trimming the integrated skew quad strength as a function of the total number of shims added

The simple linear relationship shows that the magnet can be tuned over a range of 0.1 Tesla-m/m. Beyond that range a clear saturation of the steel shims sets in.

One of the requirements for these magnets is that the Recycler vacuum not be opened to air during installation. This required that the magnet be split to install around the beam pipe. To accomplish this the upper and side magnet material was glued to the upper flux return using Loctite Depend™. The magnet was mounted on the test stand the top was removed and re-installed multiple times. Each time the magnet was measured. After the first opening the field change from 0.4711 Tesla-m/m to 0.4700 Tesla-m/m. Successive changes showed a variation of 0.0002 Tesla-m/m or 4 parts in  $10^4$ . There was no attempt to provide precision alignment between the top and bottom parts of the magnet.

## 2b. Rectangular Skew Quadrupole

A variation of the skew quadrupole was designed. This magnet required no angle cutting of the Strontium Ferrite magnets. It did require more machine work on the flux returns. Figure 3 shows the PANDIRA output for this magnet. The corners were clipped to allow closer positioning of the magnet to the adjacent beam line. This magnet was 152.4 mm in length with a gradient of 4.2 Tesla per meter. This magnet was also designed to be split apart and installed around the vacuum pipe of the recycler. Similar studies were using shorting steel were done on this type of magnet yielding similar results. The rectangular quad was the final design installed in the Recycler.

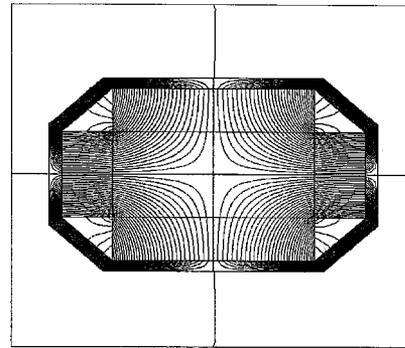


Figure 3 Skew Quad with Rectangular Bricks

## 2c. Halbach array quad

A third type of skew quad was made using a Halbach array this is a simple two magnet style skew quad as shown in figure 4. A 50.8 mm by 25.4 mm thick strontium ferrite center brick and two 25.4 by 25.4 mm side bricks were used to build the array. The predicted strength was 0.51 Tesla-m/m. The measured strength was 0.60 Tesla-m/m. The higher measured strength was due to variation in the Br of the ferrite. Similar strength tuning was used as the previous two styles of magnets.

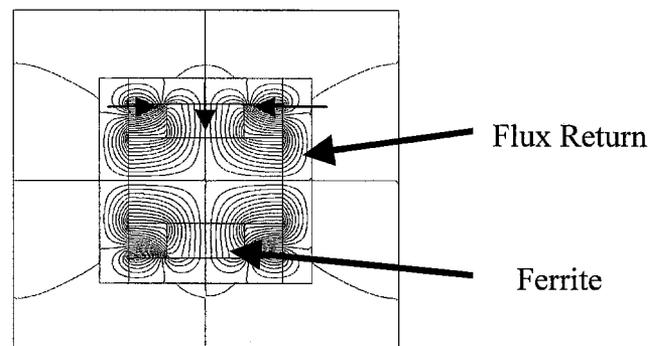


Figure 4 Halbach array skew quad arrows indicate direction of the field in the array

## 3. Sextupoles

The required integrated sextupole strength to cancel the sextupole component in each pair of gradient magnets was determined by minimizing the lattice function distortion due to the design orbit offset through the pairs of gradient magnets. The design integrated strengths,  $B''L/2$ , ranged from 1.5 to 2.5 Tesla/m, depending on lattice location. The basic design selected was a Halbach array rolled around the pipe. For the sextupole a total of 12 pieces of permanent magnet material were used. The direction

of the field rotated by 90 degrees for each magnet. Figure 5 shows a PANDIRA output of the sextupole.

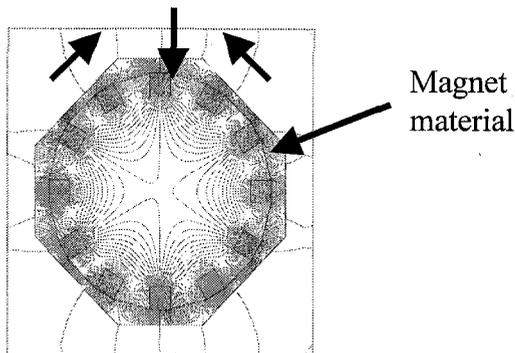


Figure 5 Sextupole field map with typical direction of Br shown

Aluminum spacers were used to separate each of the segments of magnetic material. A hole was drilled the length of each spacer to provide a place to install steel washers. These washers were used to adjust the strength of the sextupole to the desired strength. Figure 6 shows a plot of the total number of washer versus the strength of the sextupoles. A total strength change of 83% was possible by adding washers in all the holes. Some adjustments of the higher harmonics were possible by asymmetric loading of washers. This was not necessary for these sextupoles.

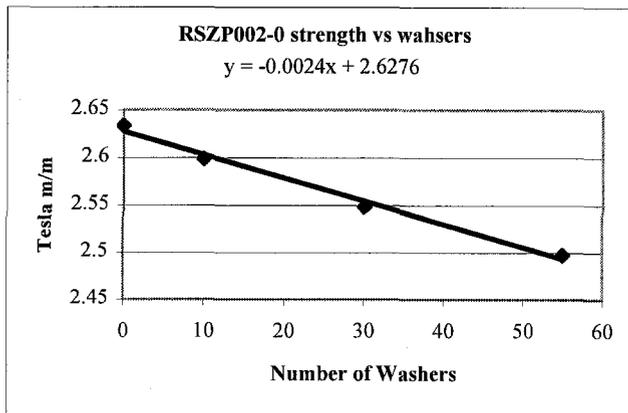


Figure 6 Trimming the integrated sextupole strength as a function of the total number of shims added

The sextupoles were designed to clamp around the beam pipe. This eliminated the need to disturb the Recycler vacuum. It did require that two different internal diameter magnets to be designed. One type fit around the 10.16 by 5.08 cm elliptical beam pipe and the other type fit around the 15.24 cm diameter bellows. Studies were

done to assure that the field did not change when the magnets were disassembled and reassemble.

To achieve the required fields the small diameter sextupole used grade 8 strontium ferrite. Each of the 12 channels used 66 mm of ferrite to achieve the desired gradient of 2.3 Tesla /meter.

The larger diameter sextupole use Neodymium Iron Boron magnets with a Br of 11800 Gauss and Hc of 16000 Orsteads part number HS 30 CV. Hitachi metals of Edmore Michigan supplied the material.

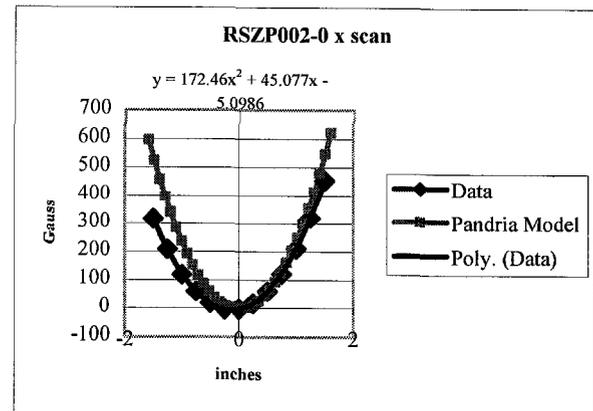


Figure 7 Hall probe scan of sextupole with Pandria model data

Figure 7 shows the PANDIRA prediction of the field at the mid plan along with a hall probe scan of the magnet. The offset in the hall probe data is due to differences in the Br of the magnet material.

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- 1) Stephen D Holmes "Status of the Fermilab Main Injector and Recycler" 1997 Particle Accelerator Conference Conf 97-46
- 2) H.D Glass, "Permanent magnets for beam lines and the recycler ring at Fermilab", 17th International Conference on High-Energy Accelerators
- 3) B. C. Brown et al., "Hybrid Permanent Magnet Gradient Dipoles for the Recycler Ring at Fermilab", Proceedings of 15th International Conference on Magnet Technology, 161, 1998.
- 4) M.P. May et al., "The Design and Construction of the Permanent Magnet Lambertson for the Recycler Ring at Fermilab," Proceedings of PAC'97, Vancouver, Canada, 1997.